TRANSACTIONS
OF THE
ILLUMINATING ENGINEERING SOCIETY

FOUNDED IN LONDON 1909

INCORPORATED 1930

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VOLUME XIX
No. 2 — 1954

32 VICTORIA ST
LONDON, SW1

Annual Subscription to Non-Members - £2.2.0
Price per Number to Non-Members - 5s. 0d.

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Application of Fluorescent Dimming Circuits

By H. H. BALLIN, Ph.D., B.Sc.(Econ.), *(Fellow)*, and W. J. VINE *(Fellow)*

Summary

The paper surveys the use of fluorescent dimming for different lighting applications. New requirements have led to the development of new circuits which are briefly discussed. A short description of the lighting equipment is followed by a consideration of some uses of dimming in industrial lighting. The potentialities of fluorescent stage lighting are discussed in the light of experience. Other applications considered include colour changing flood-lighting of buildings, outdoor illuminations and display lighting. It is concluded that fluorescent dimming has made possible new and artistic lighting effects.

(1) Introduction

The improvement in the general level of illumination in interior and exterior lighting during the last two decades has been rapid and has been made possible by the development of new and highly efficient light sources. For certain tasks a minimum illumination is demanded by law and detailed guidance on good practice is given in publications such as the I.E.S. Code. Recent research and experiment have been mainly concerned with the qualitative aspects of lighting, and architects and lighting engineers in co-operation have taken welcome steps towards integrating natural and artificial lighting in the general design of buildings. The creation of visually interesting and colourful surroundings in factory and office, as well as in places devoted to entertainment and leisure, must to no small degree depend on imaginative and flexible lighting appropriate to the specific application, but consisting as far as possible of standard components which can be easily and quickly replaced. From its introduction about fifteen years ago, the hot cathode tubular fluorescent lamp has proved a most useful light source as it combines high efficiency with long life, low brightness, and cool running, and is available in a variety of sizes and colours to meet most requirements. Its chief disadvantage is the need for relatively costly and somewhat bulky control gear which has retarded its use whenever initial capital outlay is of paramount importance.

Until a few years ago the use of tubular fluorescent lamps for certain applications was impossible owing to the absence of a simple and inexpensive method of controlling their light output, but this limitation was removed with the development in 1950 of a satisfactory dimming circuit[1]. This paper describes some of the major applications of "fluorescent dimming" and shows its limitations as well as its potentialities. Although often only tentative conclusions are possible, it is hoped that they will assist architects and lighting engineers to assess the scope and value of this development.

(2) Circuits

The conditions necessary for the successful dimming of hot cathode tubular fluorescent lamps were fully discussed by Strange[1] who described a circuit that gave adequate range and smoothness of dimming. A number of new circuits have since been developed. Some are designed to achieve the same results as the original resistive system by other means; others have been introduced for new applications where the stage lighting requirements of maximum range and smoothness do not hold.

It is not intended in this paper to give a full description of these new circuits, but only to indicate the main characteristics of some of them to assist the general understanding of the problem.

The manuscript of this paper was first received on September 3, 1953, and in revised form on October 8, 1953. The paper was presented at a meeting of the Society held in London on November 10, 1953.

(2.1) Full Range Resistor Circuits

The use of 2-ft. 40-watt lamps with 100-step resistor banks originally offered the best results. Experience, however, soon showed that it was possible to utilise the more efficient 5-ft. 80-watt lamps (Fig. 1) while still maintaining to the fullest extent smoothness and range of dimming; the luminous efficiency (excluding gear) of a 5-ft. 80-watt lamp is nearly 40 per cent. greater than that of a 2-ft. 40-watt lamp. The advantage gained by use of the larger lamps can be illustrated by considering the lighting of a 30 ft. wide stage. Assuming a single line of lamps, five 80-watt lamps will be required and these will have an average-through-life light output of 20,000 lumens. In contrast 14 2-ft. 40-watt lamps would be needed and would provide only 18,480 lumens.

Apart from this change from a circuit utilising two 2-ft. lamps in series to one of a single 80-watt lamp, the basic resistor circuit has not been fundamentally changed. Equipment has been improved and the size of dimmer boards reduced, thereby overcoming the difficulties so often encountered where space is restricted. Remote control of an installation is now possible, and as a result the ease and flexibility of fluorescent dimming now equals that of filament lamp dimming.

(2.2) Miniature Dimmers

For many applications where an adjustment of the light level by dimming is desirable, the range can be restricted and dimming can occur in steps. Prices and space limitations often call for small compact units instead of the 100-step dimmer banks. One type of equipment developed for certain industrial purposes provides five distinct steps between "full-up" and lowest position plus "black-out." Another type—intermediate between this and the 100-step dimmer—has a dimmer switch providing 20 steps.

(2.3) Colour Changing Circuits

The increasing use of fluorescent lamps has necessitated the development of a variety of "white" lamp colours, but even so there is a constant demand for other colours which, if met, would lead to a multitude of types and increase substantially manufacturing and distribution costs; moreover, for some lighting applications, the colour requirements are not constant. For example, the colour of artificial light designed to supplement natural daylight should match daylight as nearly as possible.

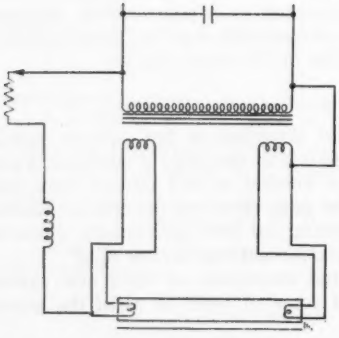

Fig. 1. Basic dimming circuit for hot cathode fluorescent lamps.

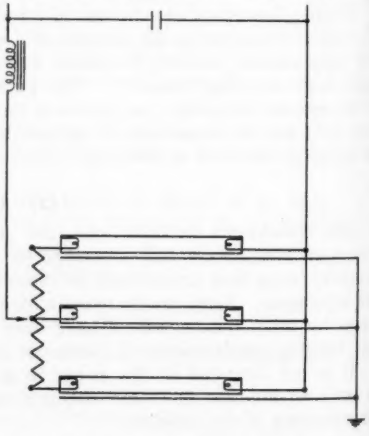

Fig. 2. Rheostatic divider circuit using 3×80-w. lamps and only one choke.

Table 1
Summary of Fluorescent Dimming Systems

Type	Smoothness of dimmer control	No. of lamps per choke	Possible applications	Method of operation	Life of dimmer component
Resistance Control 100 Steps	Good	1 off	All applications	Hand and motorised	Unlimited
20 Steps	Fair	1 off	Amateur theatrical productions; Industry	Hand only	Unlimited
5 Steps	Coarse	1 off	Display work and Industry	Hand only	Unlimited
Rheostatic Divider	Very good	3 off	Floodlighting, display and Industry	Hand and motorised	Unlimited
Thyratron Valves	Very good	1 off	All applications	Hand only as yet	Limited by valve life

but light of a warmer colour from the same installation is often desirable during the hours of darkness. Another example is in the field of display lighting where different colours may be needed at different times.

These objectives can be achieved by using two or three fluorescent lamps of different colours, dimmer controlled so that predetermined proportions of light from each contribute to the overall result. Standard 100-step resistance dimmers can be employed, but would prove too expensive for most applications. A circuit is required which provides at low cost the maximum flexibility in adjusting the proportion of light from each lamp without substantially changing the overall light output of the combination. This need has led to the development of a circuit in which three 80-watt lamps are controlled from a single choke and rheostatic divider in such a way that (a) any one of the three lamps alone is fully alight, or (b) two adjacent lamps are both contributing a proportion of the light (Fig. 2).

Where a wide range of colour combination is not required, a modified circuit is available in which only two lamps are controlled in this way, the third lamp being operated with conventional gear. The equivalent of two lamps out of three are therefor always alight, and where space is limited this alternative may be preferable.

(2.4) Thyratron Valve Control

The use of thyratrons to control fluorescent lamps has been considered for some time[2], but recent improvements in lamp quality have now made this a practical proposition. Two thyratron valves are arranged back to back on an AC supply and these act as electronic switches to control the current flow. Normal chokes are used in conjunction with the cathode heating transformers.

A small controlling resistance, used in a phase advancing sub-circuit feeding the grids, alters the moment of switching during the forward half cycle in each valve and so varies the average current in the lamps.

These valves, being inserted in the phase line of the supply and acting as high-

speed switches, can supply a number of fluorescent (or for that matter incandescent) lamps using the one small control resistance. Circuit wiring is reduced as separate feeds to each lamp are no longer necessary. Group control is effected by a small resistance. The circuit lends itself to comprehensive remote control systems where the light output from one or more groups of lamps is proportional to the displacement of the control resistance.

The major features of the circuits discussed above are summarised in Table 1.

(3) Equipment

(3.1) Lamps

As most of the dimming circuits are derived from "quick-starting" circuits it is natural that similar conditions for the satisfactory operation of fluorescent lamps apply. The lamps should be of the quick-start or instant-start type, i.e. either coated with a water repellent material and in close proximity to an earthed metal surface, or provided with a metal strip which is connected to earth. Subject to these conditions and correct installation, fluorescent lamps have given satisfactory service even in outdoor and underwater conditions, but the ambient temperature was always well above freezing point. The operation of these lamps in open fittings at temperatures below 5 deg. C. is not recommended.

(3.2) Fittings

Special stage lighting equipment has been developed, but a large variety of standard fittings can also be used. Bare lamps in concealed positions will operate satisfactorily as long as provision is made for adequate earthing.

For outdoor applications special reflectors are needed which are light in weight, simple to install and corrosion resistant. Anodized aluminium units meet these requirements most satisfactorily, but for wide angle floodlighting stove enamelled sheet steel reflectors can be used. One general purpose unit contains three lamps which may be of different colours controlled by separate dimmers The light distribution is necessarily general rather than directional (Fig. 3a). For medium range projection a single tube parabolic reflector has been designed to give the distribution shown in Fig. 3b, and banks of three fittings are necessary for three-colour effects.

It has been found that open fittings are quite satisfactory for outdoor operation even when exposed to constant water splash, but special watertight lamp holders are required. Bi-pin holders make better and more secure contact than the bayonet type whose plungers have a tendency to corrode; bi-pin 80-watt lamps have therefore been used for these applications. Additional protection, where required, can be provided by enclosing the fittings with acrylic front covers.

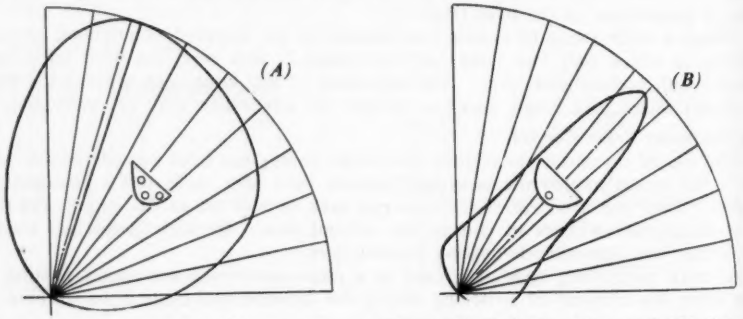

Fig. 3. Polar curves for (A) general purpose flood with 3×80-w. tubes, and (B) for one 80-w. tube.

(3·3) Control Gear

For the dimmer systems discussed in this paper, chokes and capacitors of conventional design are employed. In addition, there is a mains energised cathode heating transformer with the choke and dimmer impedance connected between the phase line and the higher voltage cathode (see Fig. 1). Specially designed dimmer transformers provide cathode heating for three 80-watt lamps, and considerably reduce the cost of gear and wiring. Where 2-ft. 40-watt lamps are needed—say for auditorium lighting—these can be operated in series from a similar type of cathode heating transformer with suitable wiring connections.

Equipment of this type is used with the 100-, 20- and 5-step dimmers as well as with the thyratron valve system (i.e., where thyratron circuit replaces the resistor section [2]), and each lamp therefore requires its own choke. With the divider rheostatic circuit, however, only one choke and one triple transformer unit is needed for three 80-watt lamps (Fig. 2).

(3·4) Dimmer Boards

These vary according to application. For stage lighting purposes, the 100-step resistor system has found most use. Ganged banks of resistors are operated from a single handle, with the usual clutch handle, colour masters, master black-out, and grand master control. Incandescent spot projectors, house lighting and other circuits can also be controlled from these boards. Portable dimmer boards have been designed to augment permanent installations; they are used mainly for short production runs and for amateur purposes. For such temporary work, portable control gear containers, floats, battens and wing floods using plug-in type wiring are most suitable.

Remote control of permanent installations has been developed, using small switch panels in conjunction with motor driven dimmers in the main board. This permits control from two or more positions, e.g., one from the usual stage position and another from the back of the auditorium.

The miniature 20- or 5-step dimmer switches are of wafer construction mounted on a common spindle, taking up to four 80-watt lamps per position. Each resistor bank can be accommodated in a space of less than 6 in. square, with a depth of only 1½ in. per 80-watt circuit, and are front mounted. They are easily built into control panels and portable equipment as required.

Fluorescent circuits can be automatically dimmed by using suitable A.C. geared motors. For simultaneous raising or lowering of the light output of all connected circuits single stroke dimmers are employed, controlled by remotely located push buttons. The time lag between "full-up" and "out" is between 10 and 20 seconds. Continuous cross fading of two colour groups is obtained with single and opposed cycle automatic dimmers, but a more economical alternative is the automatic colour mixing dimmer of the relay type, where one dimmer is used for three colour groups. By means of relays operated from switches on a camshaft, each colour group is in turn connected to the dimmer and a limited but, for many purposes, sufficient range of colour combinations is obtained[3]. For complete flexibility, drum controlled automatic dimmers should be used. Each dimmer has its own motor, which is switched on and off or reversed by a master drum controller driven by a separate motor.

(3·5) Wiring and Installation

For wiring, considerable use is made of seven-core P.V.C. flexible cable and multi-pin plugs and sockets; normal V.I.R. cables are also often used. Since fluorescent lamps are cool in operation the use of asbestos cables is not necessary. The dimmer boards should be as close as possible to their fittings to minimise cable costs. In difficult installations cable cost can sometimes be reduced by using remote control

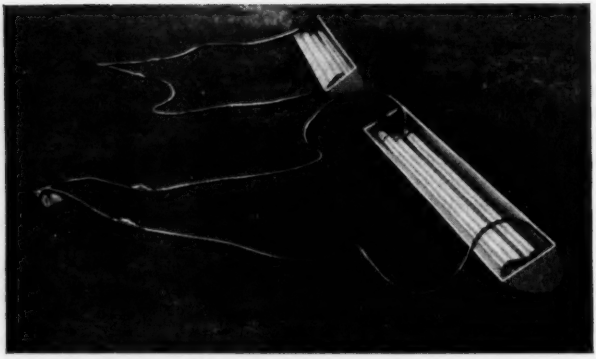

Fig. 4. Outdoor fluorescent floodlights.

stations. Where lamps are located in restricted spaces such as cornices or laylights, or for stage lighting, the chokes and P.F. capacitors can be housed in the dimmer board or in some convenient cupboard or other space.

For outdoor installations three-lamp leads and the earth connection are joined into a single seven-core flexible cable at each end of the fitting, and these connect to multi-pin weather-proof plugs and sockets (Fig. 4). These join to the cathode heating transformer and from there via further plugs and sockets to the control gear and dimmer board. These arrangements ensure full flexibility of layout with rapid and easy installation, and permit extensions and alterations to suit varying conditions, as in gardens and other outdoor situations.

(4) Industrial Applications

It is an advantage for the lighting of some industrial processes to be able to modify background and surround brightnesses, and fluorescent dimming enables this to be achieved efficiently and economically.

(4.1) Inspection Lighting

Inspection processes provide several examples where it is desirable to change the background brightness. These include the silhouette inspection on opal glazed-top benches of small components, and industrial processes in which the finished product is moved over larger luminous areas and inspection is by transmitted light. In the manufacture of cloth, a high illumination, which can be adjusted according to the type of cloth produced, is required; for inspecting the coating of photographic film, on the other hand, a very low level of illumination is needed, whose value can be adjusted to suit the speed of the film and whose colour depends on the type of film emulsion.

For such inspection processes, fluorescent lamps are housed behind an opal glass or opal acrylic sheet in a well-ventilated compartment. The dimmer control is positioned conveniently for the particular operation; usually the five-step dimmer switch gives an adequate range.

(4.2) Transport

Movement control often involves supervision from within a limited building of traffic in the dark, and it is of great help to be able to control the illumination in the control building. Examples include airport control towers, ship navigation, railway signal-boxes and coal-handling at power stations. Use of the 20-step dimmer makes smooth gradation possible, and directional and louvred fittings are

often used to prevent direct view of the lamps upsetting the partial dark adaptation of the viewer. Fluorescent lighting is ideal for such applications as it blends readily with fading daylight and avoids strain under these conditions.

The lighting of radar rooms involves similar problems and similar equipment is used.

(4·3) Laboratory Uses

Scientific research frequently requires easy adjustment of the lighting levels during experimental work. Fluorescent dimming has been used in investigations into plant and algae growth, and a recent demonstration was given at the 1953 Conversazione of the Royal Society in London.[4]

Fluorescent dimming is also used in X-ray viewing apparatus. It is necessary to vary the background brightness to allow for the differing densities of negatives and individual needs of the viewer. A 5-step miniature dimmer has been devised controlling two 15-watt lamps which are positioned behind the opal glass screen.

(5) Stage Lighting

Since fluorescent lamps were first introduced for stage lighting, the ability to provide the required degree of smooth dimming has been proved and technical doubts dispelled by operational experience. The fluorescent lamp is at its best when employed in continuous runs, and the advantages for cyclorama lighting—particularly where blue, grey or white sky effects are wanted—are now widely acknowledged. The very small distance from the cyclorama at which the equipment can be installed makes it particularly useful on difficult stages. Fluorescent lamp battens and floats provide a much higher "full-up" illumination than similar incandescent equipment, and do so at lower running cost; moreover they do not create the disturbing "colour blobs" which are difficult to avoid with tungsten lamps when various colour filters are used side by side in one unit. The rapidity of "black-out" and "snap-up" with fluorescent equipment is far greater than with incandescent lamps and has led to its use for lightning and other effects.

In the opinion of some lighting engineers general lighting of stages is out of date and has been superseded by strongly directional lighting from spotlights and front-of-house floodlights. Although directional light control of fluorescent lamps is possible to a larger degree than is generally assumed, it must be admitted that if floats, battens and wing floods became obsolete, then the application of fluorescent lamps for stage lighting would be restricted. Spectacular shows like operas and musical comedy, as well as variety, rely for their effect on colourful and flexible lighting, and a stage devoted to this kind of performance must have the fullest equipment both back-stage and in front. In straight plays, however, a lighting set with spotlights and floodlights only is conceivable and, indeed, there have been many productions in which this type of lighting was used. In such a play the rôle of fluorescent lighting would be only subsidiary and restricted to background and special effects. The skill of a producer, however, is shown, not least, in the way he achieves new visual experiences for his audience. However excellent the present concentration on directional lighting may be, the desire for change is strong enough to ensure that other methods will be adopted sooner or later It is therefore unlikely that stages will dispense with general lighting installations.

The advantages of fluorescent stage lighting were fully explained by Strange[1], who also showed that many colour requirements could be met by combinations of red, green and blue lamps. For cyclorama lighting green is not normally used, and a combination of dark blue, light blue, pink and gold lamps gives all the colours required; higher levels of illumination are possible with these combinations than with

combinations of red, blue and green lamps. The colours employed for general lighting depend on the type of show; one or two circuits use the white (3,500 deg. K) tube for maximum "full-up" effect. In addition light blue, pink, gold or ultra-violet lamps are often installed. The latter have proved outstandingly successful in variety and ice shows for "black light" effects, both on account of their efficiency and ease of operation.

Stage lighting will vary with the ideas of the producer and the type of show, but fluorescent lighting, with its colour effects, its low operating temperature and its economic advantages should find increasing application.

(6) Auditorium Lighting

The lighting of an auditorium (be it theatre, cinema or concert hall), a restaurant or a dance hall must include provision for the smooth control of lighting levels. The transition from relatively brightly lighted foyers to the semi-darkness of a concert hall, or the darkness of a theatre must be gradual if discomfort and annoyance are to be avoided (Fig. 5).

Tungsten lamps have, in the past, been widely used for auditorium lighting, but their efficiency has been very low, particularly where, for decorative reasons, small wattage lamps have been employed. Some electricity tariffs tend to discriminate against high kilowatt loading, and it will be seen from the comparison in Table 2 that the relighting of many auditoriums is as desirable economically as from the aesthetic point of view. An interesting installation using cold cathode fluorescent lighting in the auditorium of the Royal Festival Hall has been described by Hunter[5].

The lighting of the proscenium arch surrounds usually calls for the use of coloured as well as white light. A comparison of the requirements of tungsten and fluorescent installations is shown in Table 3. Fluorescent lighting has the additional advantage that it can be held at low check economically to provide primary maintained lighting, thus avoiding the need for separate wiring and equipment.

Present-day town planning provides for the creation of community centres in which a hall may serve a large number and variety of purposes. It may well be possible to

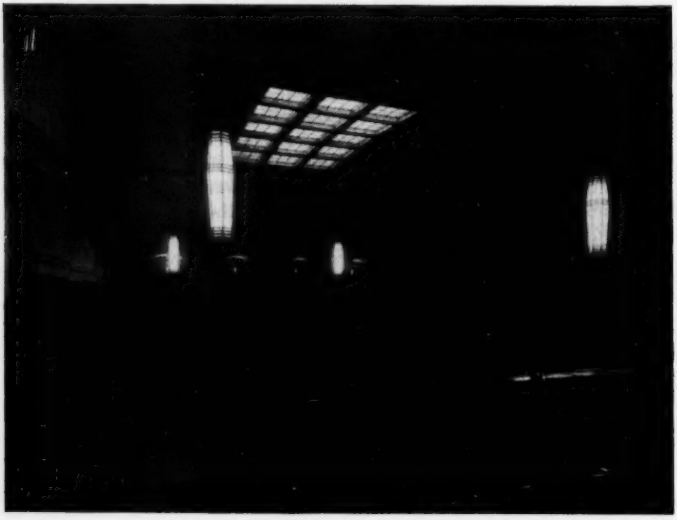

Fig. 5. Hot cathode fluorescent lighting in an auditorium.

Table 2

Auditorium Lighting

A COMPARISON FOR THE SAME LIGHT OUTPUT BETWEEN TUNGSTEN FILAMENT AND FLUORESCENT LIGHTING BASED UPON 100 FT. OF COVE OR CORNICE*

"Full up" lumens per ft. run†	230-volt single coil tungsten lamp.‡					Hot cathode fluorescent lamp (3,500 deg. K)				
				Load in kw					Load in kw	
	Lamp	Quantity	Spacing	Full up	Quarter check	Lamp	Quantity	Spacing	Full up	Quarter check
500	25w	232	5¼in.	5.8	4.8	4ft.	24	4ft. 2in.	1.3	0.41
	40w	147	8⅛in.	5.9	4.8	40w				
630	40w	185	6¼in.	7.4	6.1	2ft.	48	2ft. 1in.	2.59	0.86
	60w	105	11⅜in.	6.3	5.2	40w				
720	40w	212	5⅝in.	8.5	7.0	5ft.	18	5ft. 6⅝in.	1.8	0.6
	60w	120	10in.	7.2	5.9	80w				

* Resistance type dimmers for both installations.
† Based on average lumens through life of tungsten lamps and fluorescent lamps.
‡ Alternative equivalents are given.

Table 3

Proscenium Arch Lighting

A COMPARISON FOR THE SAME LIGHT OUTPUT BETWEEN TUNGSTEN FILAMENT AND FLUORESCENT LIGHTING FOR A 100 FT. LENGTH OF ARCH*

Average lumens (of 3 colours) per ft. run	230 volt single coil tungsten lamp					Hot cathode fluorescent lamp				
	Lamp	Filter No.	Quantity	Spacing	Average load in kw†	Lamp	Filter No.	Quantity	Spacing	Average load in kw†
252	60w	6	195	6¼in.	21.45	5ft. 80w Peach	6	18	5ft. 6⅝in.	2.7
	60w	39	195			Green	39	18		
	100w	20	195			Blue	—	18		
235	60w	6	181	6⅝in.	19.91	2ft. 40w Peach	6	48	2ft. 1in.	3.89
	60w	39	181			Green	39	48		
	100w	20	181			Blue	—	48		
181	40w	6	247	4⅞in.	17.32	4ft. 40w Peach	6	24	4ft. 2in.	1.87
	40w	39	247			Green	39	24		
	60w	20	247			Blue	—	24		

* Based upon a motor driven system of identical cycle of colour sequence.
† Excludes mechanical drive and resistance watts, but includes control gear for fluorescent.

design lighting installations which can be adjusted for the occasion, not only by controlling illumination levels, but also by controlling the colour of the lighting. This may be achieved by adding a number of pink fluorescent lamps to the dimming circuits. For lectures or exhibitions crisp, clear lighting and a high level of illumination can be arranged, while for social gatherings or dances the lighting can be altered to create an atmosphere of pleasant warmth.

(7) Colour Change Floodlighting of Buildings

A building is floodlighted to draw attention to it either because of its importance, its beauty or for commercial reasons. The choice of light source and the kind of treatment adopted depends on the character of the building, its surroundings and the presence of other well-lit buildings in the neighbourhood which might distract attention.

(7.1) Fluorescent Lamps for Floodlighting

The principles of floodlighting were discussed comparatively recently before this Society[6], but during the last year or two successful schemes using hot cathode fluorescent lamps have proved that this light source can make a useful contribution in this field. It must be emphasised that fluorescent lamps do not compete with the established high wattage light sources where high levels of illumination are required from units placed a considerable distance away, or where the nature of the building requires the use of narrow beam floodlights.

Lighting effects softer than those given by high intensity floodlights may suit certain buildings much better, and for these fluorescent floodlighting is often suitable and economical. The fluorescent lamp, being a low wattage, low brightness line source, must be fixed fairly close to the front of a building, and to achieve the best coverage should be arranged in continuous lines. The low cost of the open reflectors suitable for this type of installation and the lower cable costs resulting from the smaller electrical loading are important economic factors, particularly if the installation is temporary.

(7.2) Colour Changing

Colour change introduces movement and life into the lighting, and is therefore primarily useful where it is intended to attract attention—e.g., in the floodlighting of theatres, cinemas, restaurants and hotels. There are, moreover, many public buildings where for one reason or another static lighting would be ineffective—for instance where the available space makes more orthodox floodlighting schemes impossible. The Sophia Gardens Pavilion at Cardiff is an example. This is a modern low red-brick building, attractive in design but rather inconspicuous from normal viewing positions as it is set well back amongst trees. Approaching along the road only occasional glimpses of the building are possible and even if highly illuminated would hardly attract the attention of the passer-by. Colour change, however, draws attention to the building in a subtle and effective way. Experience has shown that in general the lower level of illumination with fluorescent floodlighting is surprisingly effective when colour changing is used, as long as no brightly lit buildings are in the immediate neighbourhood.

When choosing colours for floodlighting applications particular note must be taken of the difference in the efficiencies of fluorescent lamps as shown in Table 4.

On a white or neutral-coloured building the arrangement of red/blue/green would prove unsatisfactory owing to the great differences in efficiency of lamps of these colours; in such a scheme the green would be far too dominant. The combination of pink, blue and green tubes with green filter sleeves has given the happiest results for this type of building. If, however, the building is a red-brick structure, its reflection properties discriminate in favour of red and against green, and thus a balanced and

Table 4

COMPARISON OF TUNGSTEN FILAMENT LAMP, FLUORESCENT LAMP AND DISCHARGE SOURCE EFFICIENCIES FOR "STATIC" FLOODLIGHTING

Colour	1000w tungsten lamps		80w fluorescent lamps		Discharge source	
	Filter No.	Lm/w	Nomenclature	Lm/w	Type	Lm/w
White	—	18.35	Daylight	35.2	—	—
	—		Warmwhite	35.2	—	—
	—		White 3,500deg. K	40.0	—	—
Peach	54	13.4	Peach	31.2	—	—
Blue	19	0.62	Blue	12.0	400w MA/V	33.88
Green	23	13.6	Green	48.0		
Red	6	3.5	Red	2.5	—	—
Amber	1	15.0	Gold	27.0	140w SO/H	54.5
Pink	11	6.4	Pink	11.0	—	—

Figures are for average through life, including gear losses.

pleasing effect can be achieved. The substitution of a gold lamp for the green one, though slightly reducing the range of colour change, creates a warmer, more cheerful sequence.

Once the lamp colours have been chosen, the questions of the speed of colour sequences and the colour combinations over the surface of the building remain to be settled. The answer to the first problem depends on the type of building and the most important viewing distance. A rapid change attracts more attention, but may easily be considered garish and undesirable. On the other hand, if the change is slow many people may not realise that a change is taking place at all. Local circumstances and individual preference must determine the final choice.

Regarding the colour combinations over the building surface, it is conceivable that the whole façade may be illuminated with the same colour, but many buildings will lend themselves to a treatment whereby parts appear in different colours. This will be particularly effective in creating a feeling of depth by bringing out architectural features.

Coronation floodlighting has given much pleasure and may well have resulted in greater civic pride in local buildings. This may encourage local authorities and others to install more floodlighting in the future and fluorescent lamps will undoubtedly have their part to play.

(8) Outdoor Illuminations

The "illuminations" of various seaside towns have been an annual event for many years and their success is a testimony to the contribution lighting can make to human happiness. A description of the design and planning of such large-scale enterprises was given by Carpenter at the 1952 Conference of the Association of Public Lighting Engineers(7). The figures quoted by him, however, show that the cost of tableaux of the sizes employed by Blackpool is very high and beyond the means of many authorities.

In recent years the feeling has grown that in spite of the much-discussed British climate there is scope for open-air activities, and that the amenity value of public parks and gardens can be much increased if, instead of closing at dusk, they are illuminated at night. The success of the Leamington Spa illuminations at Jephson Gardens may encourage other towns to floodlight their trees and flowers and by suitable lighting to add new sparkle to rivers and waterfalls. The fluorescent

lighting equipment already described is suitable for this purpose. It is economical and, being flexible, allows changes to be made from season to season at very small cost.

(8.1) Trees and Natural Scenes

Fluorescent dimming was first used for outdoor floodlighting at Battersea Park during the Festival of Britain in 1951; 136 triple-lamp fittings with a loading of 30 kw. were employed[3]. Since then, experience has been gained in a considerable number of installations and has led to certain general conclusions regarding the most desirable layout. Some illumination schemes using tungsten lamps with colour filters or discharge lamps have been open to the criticism that the creation of coloured patches, frequently of violent contrast, rendered the whole picture somewhat vulgar. It is, therefore, important to treat a park or garden as a whole and to achieve a vivid yet tasteful display. The central attraction could be a group of trees with spreading foliage which may be floodlit by two banks of colour-changing fittings, one in front and the other at the back. The 500-year-old cedar in the Jephson Gardens, Leamington Spa, is an excellent example (Fig. 6).

Surrounding the central feature there may be installations of static floodlighting with a frame of unlit trees and a foreground dark except perhaps for the floodlighting of flower-beds. The location of fittings is important and should, if possible, be decided in co-operation with the head gardener. Fixing to tree branches has the great advantages that the light sources cannot be seen and that they escape the attention of children and others with destructive minds. It will, however, always be necessary to fix a considerable number of units at ground level hidden, if possible, by low bushes or flower-beds.

The desirable speed of colour changing is a matter of opinion. Clearly a distant vista viewed by fast-moving traffic must change more quickly than, for instance, the foliage roof of an open-air restaurant. A variable speed-motor is therefore an advantage to enable experiments to be carried out. Generally the units illuminating the front of a group of trees will be controlled from one board and those at the back

Fig. 6. A tree illuminated by fluorescent lamps at ground level and in the branches of the tree.

from another, and if the motors are not synchronised variety and charm will be added to the colour changes. In small installations one board can control the whole installation and by transposing the colours varied effects can be achieved. Green, pink, blue and gold lamps are used for colour-change sequences, but for static lighting the green will predominate, although it has been found that a blue lamp directed at a tree trunk adds depth and an air of mystery. In the lighting of flower-beds the use of strong colours is to be discouraged and a mixture of colder and warmer white lamps has proved most successful.

(8.2) Fountains and Waterfalls

The attraction of fountains can be greatly increased by colour-change fluorescent lighting, as is evidenced by the Stein fountain at Brighton and the fountains at Jephson Gardens, Leamington Spa[8].

For the best effect water jets should provide a quick break-up of the water into droplets so that the light is reflected and refracted within the jet; these jets should be

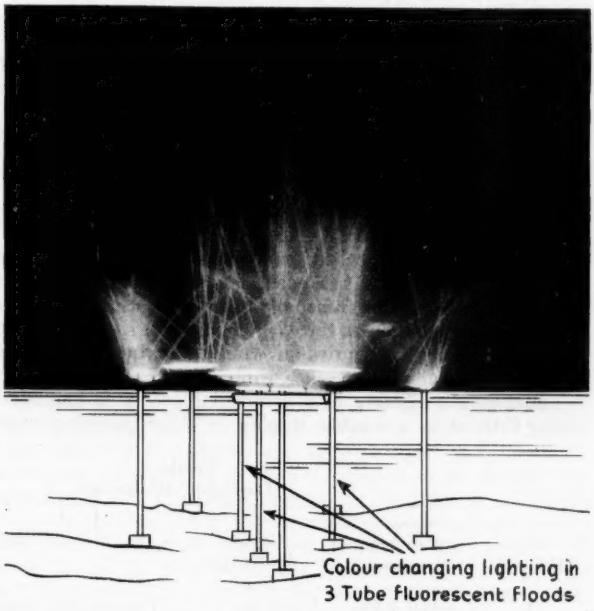

Fig. 7. Underwater colour changing fluorescent lighting at Leamington.

not too far apart or the lighting effect will be lost Cascading water, acting as overflows of the upper basins of a fountain, should not be in sheet form but again should be broken up

Fittings can be mounted close to the pipe work of the hydraulic system so that the sprays of water are illuminated immediately they emerge. Cross tracery and the more complex patterns are usually the most effective; often the best result can only be obtained by experiment. Adjustable spray equipment, hydraulically operated, can also be adapted to this system. Submerged fittings should be just below water surface level to avoid excessive transmission losses. Contrary to expectation, the spreading effect of the light due to the disturbed water surface from the spray has been found

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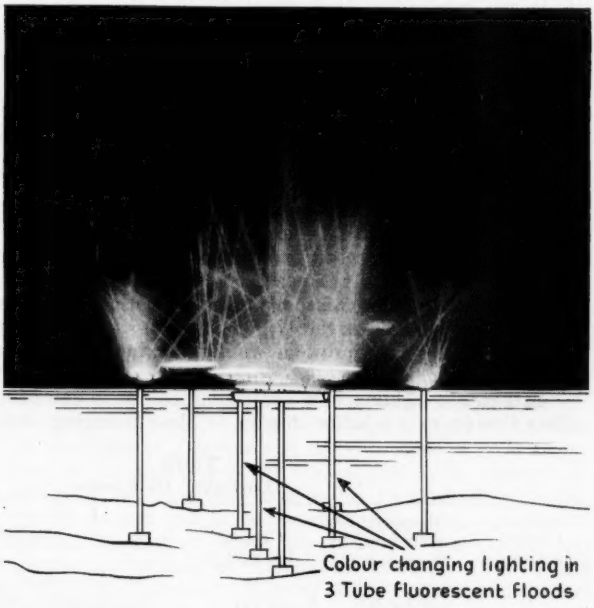

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unimportant The open reflectors usually employed are, of course, not suitable for deep immersion.

(9) Display Lighting

In the field of display lighting, which covers shops and stores, exhibitions and advertising, lighting plays a vital part. Any new developments, such as fluorescent dimming, are likely to find many uses once their possibilities are demonstrated and operation is made simple and inexpensive. The applications discussed below are a few examples which may inspire other experiments.

(9.1) Shop-Window Lighting

For lighting the windows of modern stores, general illumination by fluorescent lamps is combined with accent lighting from tungsten spot lights. Once the proportion of the two types of light source has been determined, it is necessary to decide which colour fluorescent lamp should be chosen. Certain kinds of merchandise, such as coats and day dresses, are best displayed under the light of lamps with a colour equivalent to a blackbody colour temperature of about 4,500 deg. K; other goods show to greater advantage under a warmer light which accentuates the red, and for this "mellow" or "peach" lamps are more suitable.

It is not usually practicable to restrict shop windows to a limited range of displays, nor is it convenient to change the lighting every time the window is dressed; consequently the fluorescent lighting installation is frequently not of the colour most appropriate to the display. The colour-changing circuits described in Section 2.3 have been designed to overcome this difficulty. If a three-tube divider is used, each fitting may contain a mid-white tube in the centre, a cold white tube on one side and a warm tube on the other. If the two-tube divider circuit is adopted, a white tube will be operated by conventional means and, if the fullest range is required, the colour-changing tubes should be pink and blue; alternatively, a colder and a warmer white lamp can be used. By a simple control the lighting can then be adjusted at will. Table 5 indicates some of the possible colour-control settings and their uses. It is felt that in addition to providing the most appropriate and best selling light for any particular display, a row of windows becomes more interesting if they differ in appearance from a distance.

Background lighting in a contrasting colour is one of the accepted methods of adding interest to a window display. Colour changing employing a combination of

Table 5
"Daylight" Illuminator

Control position	Approx. colour temp. (Degrees K)	General description	Possible displays
1	6,000–6,500	North sky	Pictures and Artist's materials, Furs, Silverware, White wools and linens, Cut-glass, Spring flowers, Lingerie, Household paints
2	5,000–6,000	Clouded sky	Rainwear, Shirts, Ties, Suitings (Greys and blues), Enamelware and Hardware
3	4,500	Spring and autumn effects	Spring frocks, Jewellery, Autumn flowers, Brown suitings, Black and coloured shoes
4	3,500	Summer effects	Cosmetics, Summer frocks, Foods, Sandals and Brown shoes
5	2,000–3,000	Indoor artificial light	Domestic furnishings, Furniture, Evening-wear, Chinaware

red, blue, green or gold tube circuits can, with equal advantage, be used for this purpose. By the addition of a small motor continuous colour change can be obtained. There is sometimes a tendency to dismiss such developments as "stunts," and it would certainly be unwise to expect the fullest utilisation of any equipment of this kind in one location.

With the return of the buyers' market more effort and ingenuity have been put into the presentation of merchandise, and if the control equipment for such colour changing is portable it can be moved to many different positions, both in windows and shop interiors, to add interest to some display. The vital condition that the initial cost of such equipment be moderate, is met by the circuit employed.

(9.2) Fashion Parades

Fluorescent dimming has been used to create effective and dramatic lighting for fashion parades. The "cat-walk" may be lit on either side from the walk level and owing to the low brightness of the lamps this position does not cause discomfort to mannequins or spectators. Various shades of white fluorescent tubes make possible subtle colour changing which shows the dresses in an appropriate light, but recent experience suggests that a combination of two white and one pink lamp gives the best all round results. The lighting can follow the movement of the mannequin down the walk; the two fittings on either side of, and possibly above, the mannequin at any moment are "full-up," while the fittings behind are fading and those in advance are rising. This increases the dramatic effect and focuses attention on the mannequin. It is desirable to provide overhead lighting to avoid disturbing shadows on the faces and this can be done by the use of tungsten floodlights. Apart from this one use, tungsten lamps have proved to be unnecessary. The lighting of the background can be adjusted to the character of the clothes displayed by means of coloured tubes.

(9.3) Special Effects

The possibilities of achieving interesting, even spectacular, effects by using fluorescent dimming circuits are considerable. A simple colour change will attract attention and this can be increased by arranging light sources behind as well as in front of the display piece. A message or picture behind a glass window may, for instance, appear and then fade out in the course of a few seconds simply by lighting some tubes positioned at the back. Another development on a similar principle is the so-called "Peppers Ghost" in which a smoked glass sheet is fixed at an angle of 45 deg. When lit from the front the glass acts as a mirror and shows a scene in front of it. When the rear lighting comes on the glass allows the rear display to be viewed. A number of interesting examples of this kind were used at the Festival of Britain in 1951 and those in the Country Pavilion employed fluorescent dimming equipment. The development of ultra-violet fluorescent lamps has increased the number of possibilities. A poster or design can be made to change completely if, in the course of the dimming cycle, ultra-violet tubes activate a different design in fluorescent paints or materials. Fluorescent dimming offers the display artist an ideal combination of colour, movement and change.

(10) Conclusions

This description of new dimming circuits and their applications has, it is hoped, shown that fluorescent lighting is technically capable of giving satisfactory results in a wide variety of uses, but whether it will be so used in practice depends mainly on the cost involved.

Many of the lighting problems that may be solved by fluorescent dimming can be, and sometimes have been, tackled in other ways by using other light sources.

The final criterion will always be that of cost, namely, the cost of installation and running of the fluorescent system compared with alternative methods of obtaining

the desired results. Some of these comparisons are so clearly to the advantage of the new light source that it is already rapidly establishing itself as a standard. The same reasons which have in the span of 15 years made the fluorescent lamp so popular for many industrial and commercial uses, are likely to prove its economic superiority in a much wider field, since simple and cheap methods of dimming have been found.

Many of the effects described are in the nature of refinements and may, as such, be dismissed as unnecessary luxuries. The decision on this objection lies with the user—the architect, display man and producer of entertainment. All the lighting engineer can do is to offer them new tools, new opportunities in the hope that they will prove acceptable. If this paper has succeeded in creating a better understanding of the possibilities of fluorescent dimming, it has served its purpose.

The authors wish to thank their colleagues for their help and guidance, and the directors of Thorn Electrical Industries Limited, for permission to publish the paper.

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Discussion

MR. N. C. SLATER: Some four weeks ago I gave my chairman's address, entitled "A Brighter Britain," in Nottingham. Being a "Brighter Britain" enthusiast I was very much intrigued by the depth of thought that had been put into this paper. The opener of a discussion of this type is expected to be controversial or argumentative, but there is little with which I can find fault.

On the question of a "Brighter Britain"—such as its parks, open-air theatres and the rest—we have to be very careful to avoid the garish. When Dr. Ballin was describing some of the installations I felt that with the fluorescent tubular lamp—I prefer still to call it a lamp instead of a tube—the colours available border on the rough kind of vivid colours instead of the lovely treatment of colour that artists and ordinary human beings appreciate. We should be very careful indeed about this colour approach with the fluorescent lamp. I certainly cannot agree with Dr. Ballin that there is much hope for fluorescent lighting for stage work, for the same reason.

I was intrigued by the shop window demonstration. The whole idea of a shop window is that it is a stage in itself, designed for putting on a true performance with the idea of selling merchandise. This is why the store owner is in business—he is not there to show off the lighting. There is a great future for this colour-lighted background providing it is animated to attract the individual to the window. But whatever else is done, the goods that are on sale must be shown in their true colours, otherwise Mrs. Jones will go away with what she bought as a nice green dress, but will find when she gets home that it has changed to blue. We can be brighter in our outlook with the use of the new idea.

MR. K. OLDHAM-SMITH: I noticed on the diagrams that were shown that all the tubes appeared to be of the type with an earth strip. Is it possible to arrange dimming circuits without this earth strip?

MR. S. S. BEGGS: Dr. Ballin has undoubtedly shown us that the dimming of fluorescent lamps is quite a practical proposition, and he has given a very interesting

demonstration. He put his finger right on the spot towards the end of his paper when he said that the value of these methods depends a lot on the costs. In one or two of the illustrations I could not help wondering whether the same effect could not have been obtained more easily by having, perhaps, different circuits so that some of the lamps were simply switched off instead of having an elaborate dimming set.

Sometimes one is tempted to use a new device, even though it is not the most suitable. I was concerned five years ago with the lighting of control rooms on airports, and I deliberately decided that tubular fluorescent lamps were not the right ones because I got an ample amount f light with filament lamps, and they were easy to dim down as desired. Had I been short of light the greater efficiency of the fluorescent lamp might have been an advantage, so I wonder whether this application is not an example of using fluorescent lamps for the sake of novelty rather than because they offer definite advantages.

I should like more information about the relative costs of typical installations. Dr. Ballin, naturally, has put the best case for his discharge lamps. I am not quite sure that for floodlighting, for example, they have as much advantage as he suggests, particularly for close mounting, since I should have thought that high brightness of source was required in order to get high intensities up to the top of the building. However, for many applications, especially when colour is an advantage, the fluorescent lamp certainly could compete on quite equal terms with other lamps.

MR. B. C. OSSITT: From experience of one or two installations that we have tried out on the South Coast, I can support Dr. Ballin as regards the cost. They have proved a fine attraction at night; I understand that most of them are likely to become permanent installations. They have paid for themselves time and time again in attraction value alone.

One point which Dr. Ballin did not make concerns an interesting use of fluorescent dimming in a carnival float entered in several South Coast carnivals. It was a simple float with a motor generator in its own little lorry, and the fluorescent lamp dimming on the float display made for a most effective show.

MR. A. R. MCGIBBON: The authors have shown us lamps immersed in water. I could not see whether they were enclosed inside a glass cover, or were just bare lamps. I do not know how they manage to keep the water out of the contacts.

MR. C. J. VENESS: During the demonstration one of the fluorescent lamps got up to its usual tricks of flickering. Nothing is more disconcerting than flickering fluorescent lamps. If it happened in the middle of some sort of show—and Dr. Ballin was demonstrating lighting for stage shows—it would be completely disconcerting, as it would be in a window display if it happened after normal hours when nobody was about to correct it. Is this a common fault, or is it something that would not happen very often?

MR. H. G. JENKINS: I congratulate the authors on their excellent presentation of the demonstrations. I am not without some experience in this art, and I know something of the trouble and difficulties involved. Dr. Ballin and Mr. Vine certainly told their story very well indeed.

Dr. Ballin gave the impression—I do not think deliberately—that fluorescent dimming was something that had been evolved during the last year or so. He cannot be unaware of the interesting and important dimming installations of fluorescent tubes —mainly of the cold cathode, high voltage type—which took place before and since the

war. In some ways they are much more effective than any of the hot cathode dimming which I have seen.

I was interested to hear Dr. Ballin's good opinion about the use of thyratron control, and again I would remind him that some of the pre-war installations used this method of control.

His comment about the use of dimming of fluorescent lighting in the homes was optimistic, to put it mildly. First of all, he has got to introduce fluorescent lighting into the home. Most of the domestic fluorescent installations that I have come across have had some connection with the electrical industry, and they seemed to be sources of extra-mural research rather than installations bought over the counter!

Another speaker has referred to the flicker that is associated with dimming. I am not sure whether I am thinking of the same thing, but the flicker which takes place at very low currents is undoubtedly a serious problem in fluorescent lamp dimming. I cannot help feeling that the stage people, who have been critical of fluorescent dimming, are very much opposed to it on that account.

In connection with the window display demonstration, Dr. Ballin might have pointed out that only a few fabrics glow under the action of the so-called black light. I would think that this type of source had only limited use in shop window lighting.

MR. A. E. FOTHERGILL: One of the slides illustrated a circuit using three fluorescent tubes with a small potential divider and a common choke. There are, of course, certain problems associated with the use of a common choke in discharge lamp circuits, and I would like to ask if there is any danger of unstable conditions with this arrangement. The range of dimming obtainable must be limited, and I would like to know if it can be considered adequate for all colour change applications.

In connection with the colour change sequence on the building at Cardiff, Dr. Ballin stated that the timing aspect was important. Whilst this is true it is possibly even more true of window displays, and I would like to know if the authors have any views on what the timing should be for a colour change cycle in a shop window. As an earlier speaker has emphasised, the sole purpose of a colour change is to attract attention, but if the background colours change slowly there will be little or no attraction, and I feel that some added feature on the background such as a geometric figure to emphasise colour fringes would stimulate interest. In my opinion the timing aspect is far more important in shop window display lighting than in exterior floodlighting, and I feel we would like to have more information on this point.

MR. F. BENTHAM: I agree with the last speaker that there is more to this shop window colour change. Even if white lighting or a suitable colour is concentrated on the dress or whatever object is displayed, a colour change on the background, although completely isolated, will influence the appearance of that object due to the effect of contrast. Consequently the range of colour change that can be allowed is so small that usually it is not worth the expense of putting it there.

As concerns theatre lighting, the authors take a very reasonable line. They can dim the fluorescent lamps, but they admit that they are difficult to use except for even flood lighting. They indicate cyclorama as an instance, and hope for a change in the fashion of stage lighting away from the present directional methods which are so much opposed to the use of their lamps.

In my opinion the form of lighting used in the theatre to-day is not just a matter of fashion, it is an inevitable result of the gradual learning by man to paint with light. Just as painting pictures with brush and pigment involves very slight use of washes (floods of colour), so, too, in the theatre, we have learnt the value of concentrated sources which can be localised to paint our picture.

The difficulty with fluorescent lighting is that even if you get it concentrated

in one plane, you do not get it in the other; as a result the directional fitting shown to us to-night is rather a joke. I refer to lighting of the stage proper; of course, if there were a return to the auditorium concealed cove lighting "fashion" of the inter-war years, then fluorescent lamps, hot or cold cathode, would be eminently suitable.

I am surprised that the authors consider 100 contacts for dimming sufficient, because even when the fluorescent lamps are perfectly stable they are so responsive that the dimmer steps show. Some of the demonstrations to-night tend to confirm this. I find that 130 contacts are necessary for good dimming of low wattage tungsten lamps. An enormous advantage of our "inefficient" 1,000- or 500-watt tungsten lamps for cyclorama work is the cushioning which gives a complete absence of flicker in the dawn and sunset skies they provide.

When using thyratron valves for fluorescent dimming, I find it necessary to motorise the control rheostat, because though stepless it nevertheless transmits the hand vibrations which then appear as flickers. Incidentally, the thyratron—unlike the resistance—method employs very simple wiring between dimmers and lamps, and is available without modification for hot or cold cathode or tungsten lamps, separately or combined.

MR. L. G. APPLEBEE: As one interested in stage lighting, there is one point I should like to put. We have heard about the flickering being a trouble in the theatre. Believe me, it would cause trouble! If any flickering took place on a cyclorama, I really think the roof of the theatre would come in. That sort of thing just will not be tolerated. If there was any question of any apparatus doing that sort of thing, the producer would not have it; you can never get a lost cue back again.

That is one reason why we do not use push-button switches for contactor black-outs. If anyone goes to a lift and presses the button, but the lift does not start, one can press the button again and can get away, but if anyone on the stage is supposed to be shooting the light out of a candle, and it does not go out, the tragedy becomes a comedy.

So this flickering is very important. It just cannot be allowed to happen, and it is one of the reasons why one very big theatre refused to have anything to do with fluorescent lighting on its cyclorama.

The other point concerns efficiency. We know that consumption efficiency is a very big thing to the illuminating engineer. If he can run the installation at about half the cost, it is a feather in his cap. But as regards the man who really matters in the theatre—not cheap music halls or Folies Bergere, but the real theatre—efficiency is the last thing that the producer thinks about. He is not concerned with the cost. If the lighting you have given him will not do what he wants, he has no use for it. Even if he is told, "We can run that at about 75 per cent. of the cost of the other," he would say, "I do not want that. I want the other," and he will insist on having it.

So consumption efficiency in that respect in the theatre does not count. Providing the effect gives the producer what he wants, if he can get that effect with low current consumption he is quite happy, but if the apparatus does not give the effect he is not concerned with either the cost or how much current will be consumed; he will have the apparatus that will give him what he wants to put the play over to the audience with the proper effect.

MR. VINE (in reply): Mr. Slater, in his opening remarks, referred to the question of lighting in parks and open spaces, and pleaded for reasonable colour values as distinct from the somewhat garish effects that can be produced. Fluorescent lighting, using unfiltered coloured phosphors for outdoor work, gives just those delicate shades and tints over a whole range of pastel colours, but they can be interspersed with a

number of stronger colours as and where the need arises. I suggest that when planning outdoor illuminations one should leave reasonable sections of relative darkness so that the illuminated areas can be fully appreciated. For stage lighting and display work, fluorescent lamps with filters provide stronger colours; by blending, pastel shades can be produced at will which reproduce in every respect the colours obtained by earlier means.

Mr. Slater referred also to the question of the colours in the shop window display. Unfortunately, for demonstration purposes, we were able to have only one window, and our endeavour was to show two or three effects in that one display unit. I wish we had had a large store to show the entire sequence. However, we were able to show accurate colour response on materials over the limited range of daylight variations so that the goods could be displayed to their best advantage. In addition we showed a wider colour range, which can be useful particularly for indoor lighting, and finally we showed the illuminated background. Functional lighting shows the goods as they should be displayed for the public's appraisal. The question of adding colour attraction is merely a display device which could be incorporated, say, for Christmas or at any time that it might be needed, and it could be done quite easily.

Mr. Oldham-Smith inquired about earth strips. There are two types of lamp that can be used with this equipment. One is the fluorescent lamp with an earth strip attached, and is often used in cornice runs where there is no convenient earthing facility. Alternatively, quickstart graded lamps with the proper striking qualities could be used, and they should have an earthed plate within a quarter of an inch of the lamp to give equivalent results.

In reply to Mr. Beggs the cost of this equipment is not all that much greater than standard apparatus; it depends upon how elaborate a system one wants. It must be remembered that the running cost is also to be considered, and frequently the saving with fluorescent lamps over a few years is more than sufficient to offset the increased initial cost.

On the positioning of floodlights the Town and Country Planning Authorities may object to a number of bulky filament lamp floods being installed on the fronts of buildings, but a fluorescent lamp, being relatively shallow, could be mounted on a ledge or in an inconspicuous position quite happily, and would thereby be less likely to contravene these requirements.

Mr. Ossitt referred to the question of the low loading, particularly with a mobile float which was taken through the streets. Here again the economical loading of fluorescent apparatus enabled the small generator to be carried round as well. The equipment can, of course, be used on boating lakes with a portable generator, and was so used when the "Pirates" raided Leamington Spa Gardens from the lake.

Mr. Fothergill raised the question of the common choke and circuit instability. In normal circuits the one choke, when connected to two or three lamps in parallel, is unreliable; but this particular circuit has been developed to give full stability on any one of the lamps or any pair of tubes in operation at one time. A full range of colour change is achieved and operation extremely smooth and suitable for all applications.

On the question of timing of shop window displays I think it could be used on a slow sequence, whereby Mrs. Smith, who sees a shop window which is in blue, goes to tell Mrs. Jones; but Mrs. Jones says it was red, while according to someone else it was green, with the result that they go back to have another good look at the window! Obviously, you can have a variable speed motor, and bearing in mind that people pass by in a matter of a few seconds you can have a high-speed device, almost to snap action, to compel people's attention, or you can have it relatively slow and graduated depending on the effect that is desired.

DR. BALLIN (in reply): Mr. Beggs and Mr. Jenkins referred to other possible solutions to the problem of lighting in addition to those which we have demonstrated. I fully agree, and I want to stress that it is not necessary in every case that the solution by hot cathode fluorescent lamps is the best or the only one; but we feel, in the light of what the President said in his address, that we should put before you possibilities which may or may not prove the right ones, in any particular application.

On the question of true colour, which Mr. Slater raised, this is the old question of "What is true colour?" If you buy a garment for outdoor use, you want the daylight effect. If you buy an evening dress, you are interested not in the "true" colour but what it looks like in the surroundings of the ballroom. Therefore, the need for adjustment of the colours is very real and will remain.

A point was raised about the background lighting in shop windows. While it is quite true that the background lighting must not interfere with the general effect of the lighting, nevertheless it is quite possible to have subdued lighting in the background, which is effective and at the same time stimulating.

On the question of flicker raised by some speakers, I feel that the answer is definitely clinched by Mr. Applebee's remarks. He said that if any flickering took place, the equipment would come out immediately. Well, it has not come out, and I am quite certain that where time is allowed for proper installation—instead of the two and a half hours taken to instal the several exhibits shown—it is possible to achieve perfect control of the lighting levels with fluorescent lamps right down to the degree which is required for stage lighting. We used originally 2-ft. 40-watt lamps because the range was greater, and it proved unnecessary. The fact that fluorescent lamps are quite widely used for this purpose is a sufficient answer to the point.

To return to the major point, we do not claim to "sell" fluorescent dimming for all and sundry applications. The trade could not cope with it. But it opens up tremendous new possibilities and we must explore these if we want to widen the scope of lighting. We are advising you, the lighting engineers and the users of lighting, of its development, and it is up to you to decide whether you can employ fluorescent dimming to solve some of your problems.

Additions to the List of Members

The following applicants have been duly elected by the Council to membership in the Society and their names have been added to the list of members:—

CORPORATE MEMBERS:—

Burland, W. J. .....19, Craigleith Gardens, EDINBURGH, 4.
Crofts, J. .....45, Manton Crescent, Beeston, NOTTINGHAM.
Felstead, H. W. .....18, Glen Park Avenue, Glenfield, LEICESTER.
Freedman, E. L. .....659, New South Head Road, Rose Bay, N.S.W., AUSTRALIA.
Grace, R. A. .....15, Drennan Road, Allerton, LIVERPOOL, 19.
Histon, E. L. .....44, Leaxes Park Road, NEWCASTLE-UPON-TYNE, 1.
Issott, K. V. .....9, Methley Drive, LEEDS, 7.
Polden, F. S. .....24a/24b, York Place, LEEDS, 1.
Robinson, Miss M. .....Stepping Stones, Stockton Road, Wilmslow, CHESHIRE.
Seager, P. H. .....Main Street, Gunthorpe, NOTTS.
Thomas, R. J. I. .....21, Rhondda Street, Mt. Pleasant, SWANSEA.
Timms, G. W. E. .....Milk House, Harbour Road, SWANSEA.

OVERSEAS MEMBER:—

Tuck, H. P. .....The University of Tasmania, Box 647c, G.P.O., Hobart, TASMANIA.

The "Reflected Component" in Daylighting Design

By A. DRESLER, Dr.-Ing. (*Member*)

Summary

Present-day methods of designing natural lighting in buildings are still semi-empirical. Usually the light reaching the working plane directly from the sky is the only component considered, whilst all additional light that actually becomes available through reflections and interreflections taking place outside the window and inside the room is neglected. Several attempts have been made in the past, the latest just a few months ago, to develop a more rational approach to the problem. These attempts are reviewed, and it is shown that the first element of the problem, i.e., the determination of the amount of reflected light available in any particular situation, can be solved either on a purely mathematical basis or with the help of suitable model measurements. However, because of the many variables involved, the mathematical solution is necessarily somewhat complicated if it is to yield sufficiently accurate results, whereas experimental investigations tend to deal only with a limited aspect of the whole problem. Moreover, the results obtained by either method will not be of much practical value unless they can be presented in the form of convenient tables or diagrams. Various ingenious suggestions have been made in this respect, but the method recently indicated by Biesele, Arner and Conover appears so far to be the only one which is generally applicable and sufficiently accurate, yet simple and practicable.

(1) Introduction

Contrary to a current impression, the present trend in daylight design away from the classic approach based on sky factor alone towards methods which will predict the total available daylight in a room is by no means of recent origin. It is now just 25 years since the first major contribution towards a "lumen" method of daylight design was made. Since then there has been a constant flow of publications trying to fit a complex multitude of partly interrelated variables into a design scheme of manageable proportions. All the way along one can distinguish two main avenues of approach to the problem, a theoretical one relying on calculation alone, and an experimental one using measurements in full-size or model rooms to arrive at a collection of useful data.

It is difficult to decide offhand which is basically the more promising line of attack, particularly since R. Cadiergues has shown that the computation can be carried out to a high degree of accuracy. Because of the complicated process involved, however, having the means to arrive at a result solves only half of the problem. Unless some suitable method of graphical or tabular presentation of a representative group of results is developed, there is very little hope of the average lighting engineer or architect basing his design work on "daylight factor" instead of "sky factor." Exactly the same applies to results obtained by the experimental technique, where even the greatest accumulation of individual data will be of little practical value unless they are grouped together and presented in such a way that they can be applied to any particular design problem by referring to a few graphs or, perhaps, to one or two not-too-complicated equations.

In principle, the situation does not differ from that experienced in the design of artificial lighting installations, where nobody would use the lumen method without the ready-made "Coefficient of Utilisation" tables.

What are the chances of putting daylight design on a level that is comparable to

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what we have become used to in artificial lighting for more than 30 years? Can we expect to get design tables and graphs which will allow us to predict the total daylight illumination in a room for a given set of internal as well as external conditions? To appreciate the difficulties and to assess the existing possibilities of achieving this goal this paper briefly reviews the various proposals hitherto made.

(2) The First "Lumen" Method of Daylight Design

H. G. Fruehling[1] was the first to treat the design of daylight installations on lines similar to those used in artificial lighting. His basic formula giving the average daylight factor DF_{av} in a room is as follows:

$$DF_{av} = \frac{E_{av}}{E_{ex}} = f \times \eta \times \frac{A_w}{A_F} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where:

E_{av} = average horizontal illumination on plane of reference;
E_{ex} = horizontal illumination outside from total sky of uniform luminance;
f = a window factor giving the ratio of average vertical illumination on window plane from sky to E_{ex};
η = the coefficient of utilisation, i.e., the ratio of luminous flux reaching the plane of reference and luminous flux entering the window;
A_w = window area;
A_F = floor area or area of plane of reference.

It should be noted that f refers to the direct skylight only, i.e., it neglects what we shall call the "external" interreflection resulting in additional light coming from the ground and opposite buildings.

To obtain information on η Fruehling measured the coefficient of utilisation in 30 offices, schoolrooms and laboratories varying considerably in dimensions, window sizes and reflection factors of interior walls. A_w/A_F ranged from 5.5 per cent. to 22.8 per cent. and f from 12 to 50 per cent. (theoretical maximum for a window facing an unobstructed sky); within this fairly wide range η varied between 22.5 per cent. and 53.5 per cent. only, and Fruehling considered it feasible to use an average figure of 40 per cent. for η *in all cases* when designing the natural lighting of rooms through vertical windows. This resulted in a possible error of $\pm$ 40 per cent. which was supposed to be tolerable because of the wide range in which daylight varies by its very nature and for the more or less arbitrary choice of minimum permissible average daylight factors.

Fruehling's method is easy to use in daylight design work, once f is known. For this purpose Fruehling published several tables giving figures for f for windows facing city streets or courtyards of varying size and height. It is also shown how f can be determined by graphical means, e.g., using solid-angle projection paper.

Although Fruehling's proposals were a considerable step forward, his method has not been used in practice to any great extent. This is probably mainly because the average illumination (i.e., the average daylight factor) is far less significant than the minimum daylight factor in a room lit by vertical windows, but also because his equation neglected the additional light entering the window from the ground or from opposite buildings. Moreover, by making the variable η a constant it became impossible to predict the influence which any change in the reflection factors of ceiling, walls and floor might have on the available daylight. However, Fruehling can rightly claim the credit for having shown for the first time that the lumen method of lighting design can be applied to natural lighting.

(3) First Model Measurements

When, by 1932, reliable and sufficiently sensitive photocells were available, it became possible to carry out large series of photometric measurements which nobody would have thought of undertaking with visual photometers. This was the starting point for a number of model measurements carried out in the United States and on the Continent of Europe during the following years.

J. E. Ives, F. L. Knowles and L. R. Thompson[2] used a house of normal size three miles outside Washington, D.C. They measured the horizontal illumination at 3 ft. above floor-level, with 25 to 36 observation points distributed regularly over the floor. All measurements taken inside were related to simultaneous measurements of sky luminance on clear days taken from the roof of the building. Walls and ceiling of the room were either white (78 per cent.) or black (4 per cent.). The reflection factor of the floor was approximately 13 per cent. The height of the windows could be varied from 6 to 12 ft. and the top of the window always extended to the ceiling, i.e., ceiling height was adapted to window height. Sill height was kept constant at 3 ft. above floor. The view from the windows was practically unobstructed. The authors limited themselves to showing how the total horizontal illumination and the reflected (or indirect) horizontal illumination varied with various combinations of white and black ceilings and walls for a given uniform sky luminance of 314 ft.-lamberts; they did not attempt to use their results as a starting point for the development of a daylight design method.

A first approach of this kind was left to W. Buening and W. Arndt[3], whose model measurements were made under an artificial sky of uniform luminance produced by one half of an indirectly lit Ulbricht sphere of 3 metres diameter. The special purpose of their investigation was to obtain data which would enable architects to select suitable window sizes for rooms in single- or multi-storeyed flats in built-up residential areas. The authors considered a window to be of adequate size if it provided a daylight factor of (a) 1.33 per cent. at a distance of 1.2 metres from the window on the centre line of the room normal to the window, and (b) 0.1 per cent. at the end of this centre line, i.e., at the rear wall of the room. Both daylight factors refer to a horizontal plane 1 metre above the floor.

Numerous measurements were taken for rooms of various sizes and for a wide range of external conditions, e.g., obstruction angles of opposite buildings ranging from 0 to 70 deg. and the window facing

(a) a street of infinite length,
(b) a yard open on one side,
(c) a rectangular yard, and
(d) a square yard.

From these measurements graphs were developed which indicated the window dimensions necessary to ensure the two daylight factors mentioned above. Fig. 1 gives a typical example of such a diagram which refers to a room depth of 6 metres and a window facing a street of infinite length. It should be added that the window sill is taken to be in the plane of reference, that the top of the window is 0.5 metres below the ceiling and that the distance between the walls and either side of the window should never exceed 1 metre. All the curves shown in the diagram for various combinations of window length and window breadth satisfy these conditions. Daylight design based on these tables becomes extremely simple. All one has to know, apart from a few reflection factors and the actual dimensions of the room, is the general layout of the building and its surroundings. The diagrams will then furnish the answer in the form of the necessary window dimensions which will ensure the two daylight factors, at the same time paying full regard to external obstructions as well as to internal and external interreflections.

Thus the model technique was used to produce for the first time an extremely

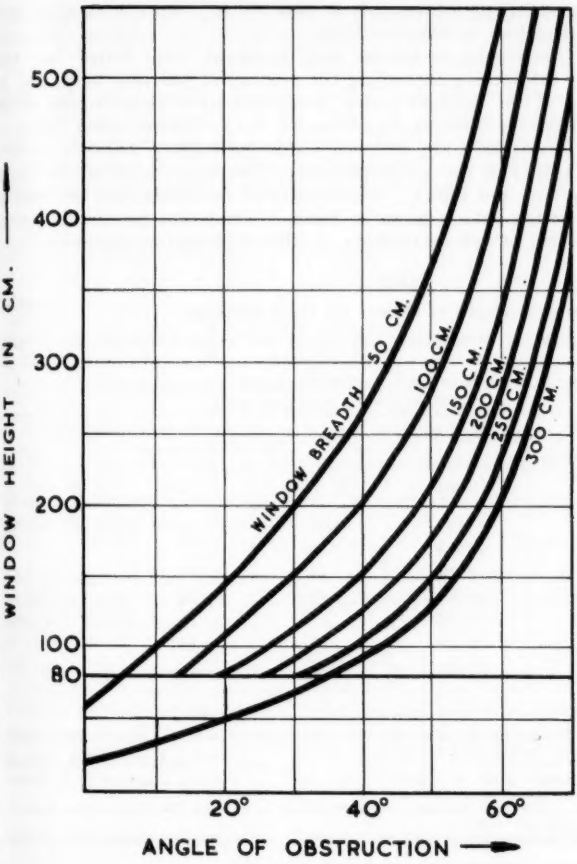

Fig. 1. A typical example of the window design diagrams developed by Buening and Arndt.

Data: Room depth 6m. Window facing a street of infinite length.

Reflection factors: Av. of ceiling, walls and floor: 50 per cent. Own and opposite house façade: 15 per cent.

simple method of daylight design which short-circuited the complex variety of factors controlling the amount of direct and reflected daylight and gave architects and lighting engineers a useful and reliable answer to their problem.

It will not by any means belittle this success if it is added that, in spite of what Buening and Arndt had achieved, there remained much to be done. In the first place, it was soon realised that the minimum daylight factor on which they had based their work was far too low for their results to be applicable to modern office or schoolroom design. Nevertheless it had been shown that the problem of improving daylight design could be tackled with the help of extensive model measurements.

However, it was not until after the Second World War that another attempt was made, using the model measurement technique, to collect information on reflected daylight in rooms lit by vertical windows. In 1949 G. Pleijel[4] published his detailed report on model measurements performed basically in the same way as those of Buening and Arndt, but with a number of definite improvements and with the

special aim of providing sufficient information to proceed to "the evolution of suitable methods for the calculation of reflected light."

Apart from giving his results in tabular and graphical form Pleijel has also tried to analyse some of the factors controlling the amount of reflected light, e.g., he states that the logarithm of the daylight factor is approximately proportional to the reflection factor of the opposite building façade as well as to the reflection factor of the walls of the room. He refrains, however, from proceeding towards a more detailed mathematical analysis of the whole problem. The main value of the report therefore lies in its diagrams and tables. An example of how these can be used to arrive at fairly general design data is given in Table I which was prepared to serve as a basis for the assessment of natural daylight in office buildings in Australia.

Table 1

Maximum Depth of Offices for Good Daylight

(Figures apply only to offices free from internal partitions and other obstructions to light)

Window width (in per cent. of length of wall)	Maximum depth of room to maintain sufficient daylight for ordinary work near rear wall				
	For unobstructed windows	For windows obstructed by buildings on other side of street, with angle of obstruction			
		10 deg.	20 deg.	30 deg.	40 deg.
30	15–17	13	11		
40	17–20	14–15	12		
50	19–23	16–18	14	10	
60	22–25	18–20	15	11	8
70	24–27	19–22	16	12	9
80	26–30	20–23	17	12	9
90	28–32	21–25	18	13	10

Notes

(i) Where a range of values is shown for maximum depth of room the smaller figures apply to room lengths under 15 ft., upper figures to room lengths exceeding 25 ft.
(ii) Table is based on a ceiling height of 9 ft., sill height 2 ft. 6 in., height of window 6 ft. For a ceiling height of 8 ft. reduce maximum depth of room by 10 per cent.; for a ceiling height of 11 ft. increase maximum room depth by 10 per cent.
(iii) Reflection factors taken as: ceiling 80 per cent., walls 55-60 per cent., floor 20-25 per cent., façade of own and opposite building 20 per cent.
(iv) Angle of obstruction is the average elevation of the "skyline" of the opposite buildings, as measured from the window head.
(v) Working position furthest from windows taken to be 2 ft. from rear wall.
(vi) Minimum daylight factor (at working positions furthest from windows) taken as 1.5 per cent.

(4) Attempts to Calculate Reflected Daylight

Pleijel says on page 3 of his report that "one of the reasons for making these tests was the impossibility of studying reflected light by means of theoretical methods." When the author of this paper read this sentence for the first time, he did not know that Cadiergues was about to publish his elegant method of computing reflected daylight by means of a set of exchange functions[5], and therefore decided to find out whether a not-too-complicated method of computing reflected daylight could be based on the formula of interreflection well known to photometrists familiar with the theory of the Ulbricht integrating sphere.

If we consider a room receiving daylight through a window and in which the reflection factors of ceiling, walls and floor are R_c, R_w and R_f respectively, the amount of luminous flux first reflected by these surfaces will be:

$$F_c R_c + F_w R_w + F_f R_f,$$

where F_c, F_w and F_f represent the fluxes reaching the various surfaces directly from

the window. $F_c + F_w + F_f$ add up to the total flux F_s entering the room. We can therefore write:

$$F_cR_c + F_wR_w + F_fR_f = aF_s \quad \ldots\ldots(2)$$

where aF_s represents the total amount of first-reflected flux.

If we are prepared to assume that all surfaces concerned will act as perfect diffusers* this amount of first-reflected flux aF_s will be evenly distributed over the whole enclosure (i.e., according to Lambert's Law) and will be partly reflected again. The amount of secondary reflected flux will equal:

$$abF_s = aF_s \left[R_c\frac{A_c}{A} + R_w\frac{A_w}{A} + R_f\frac{A_f}{A} + R_g\frac{A_g}{A} \right] \quad \ldots\ldots(3)$$

where:

A_c = area of ceiling
A_w = area of walls
A_f = area of floor
A_g = area of window glass
A = total area of room surfaces
R_g = reflection factor of glass (e.g. 0.1)

If we call the term in brackets the "average reflection factor R_{av}" of the room we get for the right side of equation (3):

$$aF_s\ R_{av}$$

The amount of flux represented by equation (3) is again distributed over the whole enclosure, and, as in the Ulbricht sphere, the total amount of reflected and inter-reflected flux is equal to:

$$aF_s\ (1 + R_{av} + R^2_{av} + \ldots.) = \frac{aF_s}{1 - R_{av}} \quad \ldots\ldots(4)$$

Because of the assumed diffuse reflectivity of all the surfaces concerned, the average luminance B_r of the enclosure produced by reflection and interreflection of F_s, which in turn produces F_r, is:

$$B_r = \frac{F_r}{\pi A} \quad \ldots\ldots(5)$$

and the horizontal illumination E_r produced by a hemisphere of luminance B_r is:

$$E_r = \pi B_r = \frac{F_r}{A} \quad \ldots\ldots(6)$$

By substituting equations (2) and (4) into equation (6), the equation:

$$E_r = \frac{F_cR_c + F_wR_w + F_fR_f}{(1 - R_{av})\ A} \quad \ldots\ldots(7)$$

can be obtained where E_r is the average horizontal illumination produced by reflection and interreflection of F_s. In equation (7) everything is readily available apart from the very vital primary flux distribution which governs F_c, F_w and F_f. Hence the usefulness of equation (7) depends entirely on having means of calculating this primary flux distribution. Ceiling, walls and floor have to be subdivided into a number of sufficiently small areas, and the illumination produced by the light entering the window has to be calculated for each of these areas using, e.g., Higbie's formulae or tables

* This assumption is not so far from the truth as one may be inclined to think, for we are dealing with the illumination produced by large surfaces often occupying almost the complete hemisphere above the plane of reference. For such conditions the illumination produced by a surface of given specular reflection will not differ appreciably from that produced by a surface having the same diffuse reflectivity.

for the computation of illumination produced by rectangular sources of uniform luminance. This is not particularly difficult as long as the luminance distribution of the outdoor surfaces as seen through the window is known, as it is, for example, for an unobstructed window facing a ground of known reflectivity, but it becomes more complicated for obstructed windows facing buildings and the like. This represents a second problem of reflection and interreflection taking place between the façades of buildings facing each other and the ground (street) between them. This "external" interreflection has to be treated on similar lines to the "internal" interreflection, and the accuracy of the results will mainly depend on how far it is possible to predict correctly the primary flux distribution throughout the "external" enclosure. Applying the same mathematical treatment as that discussed above to a street of infinite length with buildings on either side gives the following two equations:

(a) For the average luminance (B_{OB}) of the opposite façade:

$$B_{OB} = B_{sky}\, R_{OB}\, \frac{(\omega_{p1} A_B R_B + \omega_{p2} A_{OB} R_{OB} + \omega_{p3} A_G R_G)}{A(1 - R_{av})} \qquad \ldots\ldots\ldots\ldots (8)$$

where:

B_{sky} = sky luminance (unity),
R_B = reflection factor of own façade,
R_{OB} = reflection factor of opposite façade,
R_G = reflection factor of ground between own and opposite buildings,
A_B = area of own façade,
A_{OB} = area of opposite façade,
A_G = area of ground between own and opposite buildings,
A = total area of "external" enclosure ($= A_B + A_{OB} + 2A_G$)

R_{av} = average reflection factor of total "external" enclosure

$$= \frac{R_B A_B + R_{OB} A_{OB} + R_G A_G}{A}$$

ω_{p1} = average solid angle subtended by sky as seen from and projected on to own façade

ω_{p2} = average solid angle subtended by sky as seen from and projected on to opposite façade

ω_{p3} = average solid angle subtended by sky as seen from and projected on to ground between the two buildings

(b) For the average luminance (B_G) of the ground:

$$B_G = B_{sky}\, R_G\, \frac{(\omega_{p1} A_B R_B + \omega_{p2} A_{OB} R_{OB} + \omega_{p3} A_G R_G)}{A\,(1 - R_{av})} \qquad \ldots\ldots\ldots\ldots (9)$$

To check the accuracy obtainable by equations (7), (8) and (9) they were used to compute the average indirect daylight factor for the model room referred to by Pleijel in Appendix I of his report, in which the first set of tables relates to a room of 6 m. length, 4 m. width and 2.7 m. height, with a window of 1.2 m. height and 1.4 m. width built into one of the 4 x 2.7 m. walls. The window-sill is 0.9 m. above the floor. Two conditions were considered: firstly, an unobstructed view with the ground outside having a reflection factor of 20 per cent., which means that $B_G = 0.2\ B_{sky}$ (if we neglect the influence of the building containing the room on the external horizontal illumination); secondly, the window facing a street of infinite length in which the opposite

buildings form an angle of obstruction of 40 deg. To conform with Pleijel's conditions the reflection factors of the room walls and of the façades were varied from 84 per cent. over 58, 35, 20 to 0 per cent.

The results of the calculation for the unobstructed sky are shown in Table 2.

Table 2
Computed and Measured Average Indirect Daylight Factor for Pleijel's Model Room with Unobstructed View

R_w	Av. Ind. DF. computed	Av. Ind. DF. measured	Computed / Measured
0.84	1.99	1.75	1.14
0.58	1.17	1.18	0.99
0.35	0.69	0.87	0.79
0.20	0.53	0.72	0.74
0	0.31	0.54	0.57

The computed average indirect daylight factors agree fairly well with those measured, particularly in the upper range of wall reflectivities. In the street of infinite length the majority of the computed figures were in reasonable agreement with those measured, the exceptions being those for a fairly dark room opposite very bright buildings, where Pleijel's figures are much higher than those calculated.

On the whole, it can be said that it is possible to compute the order of magnitude of the reflected daylight by means of a set of relatively simple equations. It is, however, also possible, at least for a limited range of conditions, to simplify equation (7) still further, without noticeably affecting the accuracy of the results.

W. Arndt[6] has recommended the use of a formula which is based on the same general assumptions as those given in equations (7), (8) and (9), but does not require the calculation of the primary flux distribution inside the room. This formula is as follows:

$$\text{Av. Ind. DF.} = \frac{E_w}{E_{ex}} \times \frac{A_w}{A_r} \times \frac{R_{av}}{1-R_{av}} \qquad \text{.....(10)}$$

where:

E_w = vertical illumination on window
E_{ex} = horizontal illumination under unobstructed sky
A_w = window area
A_r = total room area (ceiling, walls and floor)
R_{av} = average reflection factor of ceiling, walls and floor

In this equation E_w is the only quantity that is not always readily available. For the unobstructed sky it amounts to

$$0.5E_{ex}(1 + R_G);$$

where obstructions are present it can be computed by making appropriate use of equations (8) and (9).

To give an indication of the usefulness of Arndt's formula it has been applied to Pleijel's model room for the two special conditions considered before. The results are given in Fig. 2 where the ratios of computed and measured daylight factors have been plotted against the wall reflectivity. The various curves apply to various reflection factors of the building façades and to the unobstructed view. Since the reflection factor of the façades is likely to be in the range of 20 to 35 per cent., the curves show that for wall reflectivities of 25 to 55 per cent. the computed figures will not differ by more than ± 20 per cent. from the measured ones. This applies to the unobstructed

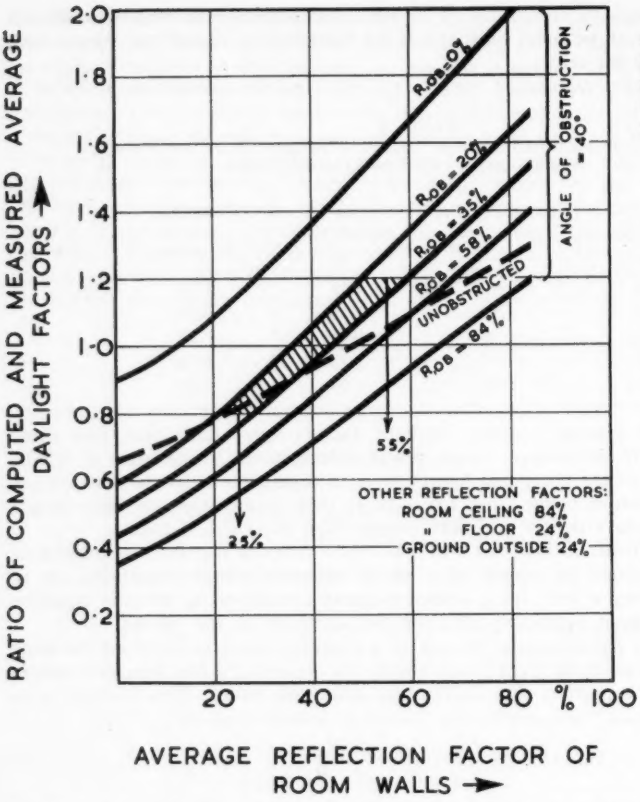

Fig. 2. Arndt's formula for reflected daylight compared with some of Pleijel's model measurements.

as well as the obstructed view. Hence Arndt's formula is, in fact, a very useful tool to calculate the average amount of reflected daylight in a room lit by vertical windows on one side.

It was mentioned before that frequently the minimum amount of daylight in a room near the rear wall is more significant than the average value for the entire plane of reference. Bearing this in mind, R. O. Phillips[7] has used the measurements reported by Ives, Knowles and Thompson and those of Pleijel to develop a method for computing the amount of reflected daylight at points near the rear wall of a square or nearly square room lit by unobstructed windows in one wall. Phillips' method, which should be of particular value for the design of modern schoolrooms, is explained in Fig. 3, taken from his paper. It will be seen that the computed figures for the reflected daylight factor are very close to those measured.

(5) The Latest "Lumen" Method of Daylight Design

The foregoing section will have shown that, although we have quite an amount of information on reflected daylight at our disposal, we still lack a uniformly applicable set of design tables or diagrams. Quite recently, however, R. J. Biesele, jun., W. J. Arner and W. E. Conover[8] have published a paper giving some of their results based

on model measurements under an artificial sky. This is remarkable not so much for the actual amount of information it provides, but for the interesting system the authors have developed for presenting their data. For the time being their investigation has been limited to unobstructed windows in square rooms and in rectangular rooms having the windows in one of the longer sides. Within this framework, however, a very promising design method has been produced.

The American authors introduce two new concepts :—

(a) the window index, and

(b) the illumination coefficient.

The window index accounts for room geometry in much the same way as the room index does in the Harrison-Anderson Coefficient-of-Utilisation method. The illumination coefficient closely corresponds to the coefficient of utilisation itself, since it is the ratio:—

$$\frac{\text{lumens reaching the work plane}}{\text{lumens incident on nominal window area}}$$

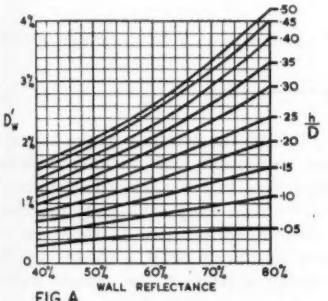

FIG. A

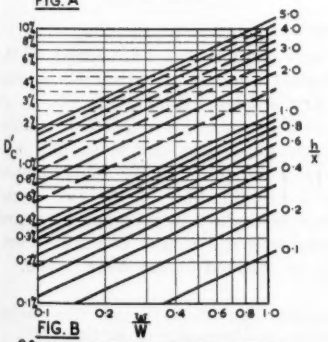

FIG. B

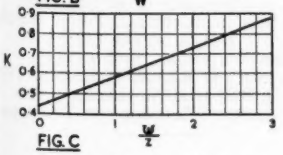

FIG. C

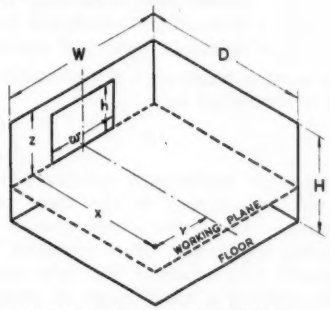

FIG. D. ROOM DIMENSIONS.

EXAMPLE

HEIGHT (H) = 8'-0" WIDTH (W) = DEPTH (D) = 14'-0"
WINDOW HEIGHT (h) = 4'-0" WINDOW WIDTH (w) = 6'-3"
REFERENCE POINT P IS 2'-0" FROM WALLS, 2'-9" FROM FLOOR.
x = 12'-0" y = 5'-0" z = 5'-3".

D.F. REFLECTED FROM WALLS $(D_w) = \frac{w}{W} \times D'_w$ (FROM FIG. A)

REFLECTANCE OF WALLS = 80% $\frac{h}{D} = \frac{4}{14} = 0{\cdot}29$

$D'_w = 2{\cdot}8$. $D_w = \frac{6{\cdot}25}{14} \times 2{\cdot}8$

$= 0{\cdot}45 \times 2{\cdot}8 = 1{\cdot}26\%$

D.F. REFLECTED FROM CEILING $(D_c) = K \times D'_c$ (FROM FIGS. B & C)

REFLECTANCE OF CEILING = 80% $\frac{w}{W} = \frac{6{\cdot}25}{14} = 0{\cdot}45$. $\frac{h}{x} = \frac{4}{12} = 0{\cdot}33$

$D_c = K \times D'_c$ $\frac{w}{z} = \frac{6{\cdot}25}{5{\cdot}25} = 1{\cdot}2$

$= 0{\cdot}61 \times 0{\cdot}4 = 0{\cdot}24\%$

COMPARISON WITH OBSERVED VALUES (UNGLAZED WINDOW)

	OBSERVED	OBS. LESS 20%	CALCULATED
D_w REFL. FROM WALLS	1·78	1·42	1·26
D_c REFL. FROM CEILING	0·22	0·18	0·24
TOTAL REFLECTED D.F.	2·00	1·60	1·50

Fig. 3. Phillips's method of computing reflected daylight factor in square rooms with white ceilings.

Both concepts are applied firstly to the light reaching the window directly from the sky, and secondly to the light coming from the ground.

If the equation used by Biesele, Arner and Conover to arrive at the amount of daylight available is expressed in terms of total daylight factor DF for an unobstructed view, we get:

$$DF = \frac{E_{ws} A_w T_g T_w MF}{E_{ex} A_f} (K_S + R_G K_G) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where:

E_{ws} = vertical illumination on window from sky alone,
E_{ex} = horizontal illumination from total unobstructed sky,
A_w = window area (masonry opening)
A_f = floor area (or working plane)
T_g = transmission factor of glazing medium for diffuse incident light,
T_w = ratio of clear window opening to masonry opening,
MF = maintenance factor (if wanted),
K_S = illumination co-efficient for light from sky.
K_G = illumination co-efficient for light from ground,
R_G = reflection factor of ground.

If design work is based on a sky of uniform luminance, $E_{ws} = 0.5\, E_{ex}$ and equation (11) can be simplified to:

$$DF = \frac{0.5\, A_w T_g T_w MF}{A_f} (K_S + R_G K_G) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

There is no reason why equations (11) and (12) and the window index concept should not be adapted to the more complicated conditions of various external obstructions. The authors have already shown that they can be applied to skies of non-uniform luminance. It is therefore to be hoped that they will continue their investigations and assemble the data which are needed to prepare further sets of diagrams covering a wider range of conditions than has been dealt with so far. A really practicable and useful method of daylight design appears to be almost within reach.

(6) Conclusions

In the introduction it was stated that what was wanted was knowledge of the chances of putting daylight design on an equivalent footing to artificial lighting design. Twenty-five years have passed since the first modest efforts were made, yet in spite of the enormous amount of work done in the meantime a perfect solution has still not been achieved, although we have a fairly good idea how it should look. It also appears reasonably clear that the question whether a purely mathematical approach, a purely experimental investigation, or a combination of the two is the most promising way to tackle the problem is now of secondary importance compared with the main task of finding the right way of presenting the results in usable form. There is every reason to expect that this goal will be reached in the near future.

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Printed by
ARGUS PRESS, LTD.,
Temple-avenue and
Tudor-street,
London, E.C.4,
England.